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The Discovery of a Planetary Companion to 16 Cygni B

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ABSTRACT

High precision radial velocity observations of the solar-type star 16 Cygni B (HR 7504, HD 186427), taken at McDonald Observatory and at Lick Observatory, have each independently discovered periodic radial-velocity variations indicating the presence of a Jovian-mass companion to this star. The orbital fit to the combined McDonald and Lick data gives a period of 800.8 days, a velocity amplitude (K) of $43.9\,\mathrm{m\,s^{-1}}$, and an eccentricity of 0.63. This is the largest eccentricity of any planetary system discovered so far. Assuming that 16 Cygni B has a mass of $1.0\mathrm{M}_{\odot}$, the mass function then implies a mass for the companion of $1.5/\sin i$ Jupiter masses. While the mass of this object is well within the range expected for planets, the large orbital eccentricity cannot be explained simply by the standard model of growth of planets in a protostellar disk. It is possible that this object was formed in the normal manner with a low eccentricity orbit, and has undergone post-formational orbital evolution, either through the same process which formed the "massive eccentric" planets around 70 Virginis and HD114762, or by gravitational interactions with the companion star 16 Cygni A. It is also possible that the object is an extremely low mass brown dwarf, formed through fragmentation of the collapsing protostar. We explore a possible connection between stellar photospheric Li depletion, pre-main sequence stellar rotation, the presence of a massive proto-planetary disk, and the formation of a planetary companion.

Subject headings: planetary systems – stars: individual (HR 7504)

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1. Introduction

A decade-long effort to detect sub-stellar companions to solar-type stars by radial-velocity techniques gave the first tantalizing hints with the discovery of a low-mass object in orbit around HD 114762 by Latham *et al.* (1989) (cf. Cochran *et al.* 1991; Williams 1996). Several more years of intense effort by various groups (Walker *et al.* 1995; McMillan *et al.* 1994; Cochran & Hatzes 1994; Marcy & Butler 1992; Mayor *et al.* 1996) have finally achieved a stunning success beginning with the discovery of radial-velocity variations implying the presence of a planetary companion to 51 Pegasi (Mayor & Queloz 1995; Marcy *et al.* 1997), followed in short order by the detection of companions to 70 Virginis (Marcy & Butler 1996), 47 Ursae Majoris (Butler & Marcy 1996), ρ^1 Cancri, τ Boötes, υ Andromedae (Butler *et al.* 1996a), and the tantalizing but unconfirmed astrometric companion to Lalande 21185 (Gatewood 1996). The systems discovered so far can be categorized roughly into three different classes: 1) the "51-Peg" type planets (the companions to 51 Peg, 55 Cnc, τ Boo, and υ And) which have minimum masses around one Jovian mass and orbital periods of several days, 2) the "massive eccentric" objects around HD114762 and 70 Vir, with minimum masses of 6-10 M_J, semi-major axes of 0.4–0.5 AU, and orbital eccentricities of 0.3–0.4, and 3) the "pseudo-Jovian" planets around 47 UMa and Lalande 21185, with low eccentricity, masses up to a few Jovian masses, and semi-major axes over 2 AU. None of these systems resemble our own solar system very closely; they all have a Jovian planet much closer to the parent star. However, there are strong observational selection effects which led to the discovery of these types of system before Jovian planets in wider orbits are detected. Since the observed stellar radial-velocity signal is proportional to the companion object mass, and is inversely proportional to the square root of the semi-major axis, massive planets in close orbits will give the largest stellar reflex velocities and thus will be the first systems detected. The detection of systems such as our own can be done with the precision of current surveys, but will require a longer baseline of observations.

We report here the detection of a planetary-mass companion to the solar-type star 16 Cygni B, the secondary star of the 16 Cygni triple star system. This object has a minimum mass well within the range of that expected on theoretical grounds for "planets", a semi-major axis which places the object near the "habitable zone" (Kasting *et al.* 1993), but with an extremely large orbital eccentricity. The low mass, coupled with the high eccentricity, makes this planetary companion unlike any of the previously discovered systems.

2. Observations

Following the inspiration of the pioneering precise radial-velocity program of Campbell and Walker (Campbell & Walker 1979; Campbell *et al.* 1988), three different high-precision radial velocity programs started major surveys for sub-stellar companions to nearby solar-type stars in 1987 (McMillan *et al.* 1994; Cochran & Hatzes 1994; Marcy & Butler 1992). The Lick Observatory and McDonald Observatory programs both included the star 16 Cygni B (HR 7504, SAO 31899, HD 186427, BD+50 2848) in their surveys. This is the secondary star in a system comprising a pair of G dwarfs in a wide visual binary, and a distant M dwarf. Table 1 compares both 16 Cygni A and 16 Cygni B to the Sun. Both of the G dwarf stars in the 16 Cygni system have effective temperatures, masses, surface gravities, and heavy element abundances very close to the solar value. This clearly demonstrates why both stars are widely regarded as excellent "solar-analog" stars (Hardorp 1978; Cayrel de Strobel *et al.* 1981; Friel *et al.* 1993; Gray 1995). The spectrum of 16 Cygni B is almost identical to that of the Sun, making this star virtually a solar twin.

The observational techniques used in the Lick and McDonald surveys to achieve extremely high radial-velocity precision are discussed in detail by Marcy and Butler (1992) and by Cochran and Hatzes (1994) respectively. The McDonald survey started in 1987 using the telluric O_2 at 6300Å as a high-precision radial-velocity metric (Griffin & Griffin 1973). The survey switched to the use of an I_2 gas absorption cell as the velocity metric in October 1990 because of concerns over possible long-term systematic errors related to the use of the telluric O_2 lines. Although all of the McDonald data are self-consistent, and the derived orbital solution for 16 Cygni B does not depend on the inclusion or exclusion of the O_2 based data, we have decided to restrict the analysis to only the I_2 based data. The primary reason is that the use of an I_2 cell allows modeling of temporal and spatial variations of the instrumental point-spread function (Valenti *et al.* 1995). Such modeling is vital to improve the precision of these measurements. The McDonald Observations were obtained with the "6-foot" camera of the 2.7 m Harlan J. Smith Telescope coudé spectrograph. All of the Lick data use an I_2 cell as the velocity metric. Lick Observatory data were obtained with the Hamilton Echelle spectrograph, fed by either the 3 m Shane Telescope or by the Coudé Auxiliary Telescope.

During 1996, both the McDonald and the Lick groups each separately became convinced of the reality of their observed radial velocity variations of 16 Cyg B, and were able to obtain totally independent orbital solutions. We became aware of each others' work on this star, and found that these separate orbital solutions agreed to within the uncertainties. We then decided to combine all of the data into a joint solution. The measured relative radial velocities from McDonald Observatory are given in table 2, and the Lick velocities

are given in table 3. Each of the two separate data sets had an independent and arbitrary zero-point. In the combined orbital solution, we left the velocity offset between the data sets as a free parameter. The values given in Tables 2 and 3 have been corrected for this velocity offset. Thus, they are on the same zero-point. The uncertainties for the Lick data are computed from the rms scatter of the ~ 700 independent 2Å wide chunks into which the spectrum was divided for analysis of the spectrograph point-spread function (cf. Butler *et al.* 1996b). The McDonald data were obtained at significantly higher spectral resolution ($R = 210,000$ as opposed to $R = 62,000$ for the Lick data). However, this configuration of the McDonald spectrograph was able to record only a 9Å wide section of a single echelle order near 5200Å. These McDonald data thus have somewhat lower measurement precision than the Lick data. 16 Cyg B is the faintest star on the McDonald program list, and the velocity precision on this star is limited by photon statistics. Empirical estimates of the velocity precision obtained from McDonald data as a function of photon flux agree well with the uncertainties computed following the derivation of Butler *et al.* (1996b). The error bars on each McDonald measurement listed in table 2 were computed in this manner from the observed flux in each spectrum.

3. Orbital Solution

The weighted orbital solution for the combined Lick and McDonald data is given in table 4. This solution agrees very well with the orbital solutions derived separately from each independent data set. If we adopt a mass for 16 Cyg B of $1.0\mathrm{M}_\odot$ (Friel *et al.* 1993), this solution gives a planetary orbital semi-major axis of 1.6 AU, and $m_P \sin i = 1.5 m_J$. Figure 1 shows all of the individual velocity measurements as a function of time. The solid line is the radial velocity curve from the orbital solution. The cyclic repetition of a strongly asymmetric radial velocity variation is quite obvious from simple inspection of the raw data in figure 1. This asymmetric, almost sawtooth, variation in radial velocity is a direct result of the large orbital eccentricity. The steeply changing portion of the velocity curve corresponds to periastron passages. A circular orbit would give a sine wave.

A Lomb-Scargle periodogram analysis (Scargle 1982; Horne & Baliunas 1986) of the data gives a large peak at a period of 824 days, in excellent agreement with the orbital solution. The false-alarm probability of this peak is 2.7×10^{-8}, ruling out noise fluctuations as the cause of the observed variations. Furthermore, it is totally inconceivable that noise would conspire to give exactly the same apparent false signal in both independent data sets. The spectral window function shows that this period is not a spectral alias of some other period.

Figure 2 shows the observed Lick and McDonald radial velocity variations of 16 Cygni A, the other star of the wide binary in the 16 Cygni system. This star clearly does not show the large radial velocity variations which are easily evident in the 16 Cygni B data. The 16 Cyg A velocities are consistent with a flat line, indicative of no variations at all. We would think that if the observed 16 Cygni B variations were the result of some unknown systematic error which somehow managed to give exactly the same periodic signal in both data sets, then such a systematic error should also affect observations of 16 Cygni A, which is only 39 arcsec away from B and was observed with virtually the same temporal sampling. A Lomb-Scargle periodogram of the 16 Cygni A data gives no peak with a false-alarm probability greater than 0.14, clearly demonstrating the lack of radial-velocity variability in this star.

The large period and the amplitude of the radial velocity curve of 16 Cygni B argue strongly for orbital motion as the cause of the observed velocity variations. An integration of the radial velocity curve would imply a a radius variation of 7.4×10^{10} cm, if one assumes the velocity variability were due to simple radial pulsations. This variation is slightly larger than the radius of the star, and is easily excluded by the lack of any observed photometric variability of 16 Cyg B. Moreover, the period of the radial fundamental for a $1.0\mathrm{M}_{\odot}$ main-sequence star is of order 1 hour (Cox 1980), far different from the observed 801 day radial-velocity period.

Non-radial pulsations may be similarly excluded. Because 16 Cygni B is a solar twin, we would expect it to have a very low-amplitude (less than $1\,\mathrm{m\,s^{-1}}$) p-mode oscillation spectrum centered near periods of 5 minutes. Similarly, its g-mode spectrum (if present at all) should have periods around 30-40 minutes, and amplitudes far less than we observe. Non-radial pulsations also may be ruled out based on the lack of spectral line profile variations of an amplitude sufficient to cause the observed RV variations (cf. Hatzes 1996; Hatzes *et al.* 1996).

The companion object to 16 Cygni B is quite unlike any other substellar object found so far. Figure 3 shows the distribution of orbital eccentricity as a function of minimum mass for the known substellar companions to solar-type stars (thus excluding the "pulsar planets"). The sample comprises Jupiter and Saturn from our own solar system, the possible planetary objects discussed in Section 1, as well as brown dwarf companions found in the CfA survey (Mazeh *et al.* 1996b) and the Geneva survey (Mayor *et al.* 1996). This figure immediately shows that the companion to 16 Cygni B is unique in its combination of low mass and very large orbital eccentricity. There is a clustering of objects around Jupiter with low mass and low eccentricity. It is tempting to think of all of these as true Jovian planets. There is a second group of objects with significantly higher masses and a wide range of

orbital eccentricities – characteristics that we would expect for brown dwarf secondaries in binary star systems. The companion to 16 Cyg B sits alone in this diagram, with a mass solidly in the range expected for planets, but with a very large orbital eccentricity. Its nearest neighbors in this figure, the two "massive eccentric" objects around HD114762 and 70 Vir, have $m \sin i$ five times larger, semi-major axes a factor of three smaller, and eccentricities about half of the 16 Cyg B companion. This new object around 16 Cyg B may represent an extreme case of the massive eccentric planets (perhaps viewed at low $\sin i$), an ultra-low mass brown dwarf, a "normal" planet which was formed in the normal manner with low orbital eccentricity but was perturbed into a much higher eccentricity, or it may represent yet another class of planetary-mass companions to solar-type stars.

4. Discussion

The current paradigm for planetary system formation (Podolak *et al.* 1993) which is based on the archetype of our own solar system, builds planets by accretion processes in a protoplanetary disk surrounding a newly formed star. The first step in the formation of Jovian-mass gas-giant planets is the growth of a rock-ice core in the disk. The most massive proto-planetary object will experience a runaway growth, sweeping up other smaller nearby planetesimals. When an object reaches a mass of 10-20 earth masses, its gravity is sufficient to capture gas in the disk, resulting in the very rapid growth of a deep gaseous envelope. This general model has been fine-tuned to produce planetary systems like our own, with a dominant gas-giant planet in a low eccentricity orbit at about 5 AU, other smaller gas-giant planets exterior to that, and smaller rocky bodies interior.

While such a model is probably able to form the pseudo-Jovian planets around 47 UMa and Lalande 21185 with some minor adjustments, this model is unable to explain either the "51-Peg" type planets or the "massive-eccentric" systems. Lin, Bodenheimer, and Richardson (1996) suggested that the 51-Peg type planets might be formed by the inward orbital migration of a gas-giant planet originally formed at much larger distances according to the conventional paradigm. This idea has been explored further by Trilling *et al.* (1996). Tidal interactions will transfer angular momentum from the planet to the disk exterior to its orbit, causing it to spiral slowly toward the star. The inward migration is stopped at about 0.05 AU either by tidal interactions with the spin of the star or by the clearing of the inner disk by the stellar magnetosphere.

Both of these mechanisms will produce planets in low eccentricity orbits. Indeed, any planet formed in a classical circumstellar disk should start its life in a nearly circular orbit. Tidal interactions between the disk and the planet will tend to circularize the orbit

quickly. Stellar companion objects, however, can have a very wide range of eccentricities and semi-major axes (Duquennoy & Mayor 1991). One possible explanation of these three low-mass eccentric objects is that they simply represent the low mass end of the brown-dwarf mass function. If this is true, then this mass function is remarkably flat through the range 0.001–0.080 $M_\odot$, and the process of binary star formation can produce systems with mass rations of 10^2 to 10^3.

An alternative explanation for the formation of the massive eccentric planets was suggested by Lin and Ida (1996). They demonstrated that if several Jovian-mass objects can form within the context of the classical paradigm at semimajor axes greater than $\sim$1 AU in a somewhat massive disk, then such a system might evolve into the types of systems we find in 70 Vir and HD114762. Numerical integrations of the orbital evolution showed that such systems will be stable while the disk is still present, but after disk dissipation the mutual gravitational perturbations of these planets on each other will often cause the system to become chaotic. The orbital eccentricities of the planets will increase and their orbits will begin to cross. At that point, the system will evolve rapidly, as the planets will collide and merge. The end result is typically a massive inner planet with a large eccentricity and small semi-major axis, sometimes accompanied by other planets in much more distant orbits. Such a scenario might provide a plausible explanation for the low-mass eccentric companion we have found to 16 Cyg B. Alternatively, large eccentricities in massive planets may be excited by the protoplanetary disk itself. Lindblad resonances in the disk material may overcome the usual dynamical damping to augment the eccentricity (Artymowicz & Lubow 1996).

The presence of the companion to 16 Cyg B around the secondary star in a binary system offers interesting additional possible explanations for its large eccentricity. The current projected separation of 16 Cyg A and B is about 39 arcsec, which corresponds to 835 AU at the parallax of 0.0467 arcsec (van Altena *et al.* 1991). The orbit of 16 Cyg A and B about each other is very poorly determined, as reliable astrometric data covers only a very short arc of the orbit. An orbital solution was attempted by Romanenko (1994) using the method of apparent-motion parameters, but it is uncertain how reliable this solution is. Most of the analytic investigations into the stability of planets in binary star systems have been within the context of the restricted three-body problem. Many of the later numerical studies have considered rather short integrations. According to the classical analytical studies, the planet around 16 Cyg B should be stable as long as the stellar semi-major axis is greater than about 10 AU, which is certainly the case given the present separation of the stars. A more detailed numerical investigation by Holman and Wiegert (1996) derived an expression for the critical planetary semimajor axis for stability as a function of the binary eccentricity, mass ratio, and semi-major axis. Applying this to the 16 Cyg system, the

planet should be stable (i.e. it does not become unbound) for almost all plausible values of stellar semi-major axis and eccentricity, provided the relative inclination of the stellar and planetary orbits is not extremely large. However, as was pointed out by Wiegert and Holman (1996) in their study of the stability of planets in the α Centauri system, if the inclination of the planetary orbit with respect to the stellar orbit is near 90°, then the planet can easily be lost from the system. Even if the planetary orbit is "stable", it is still quite possible for the stellar companion to strongly influence the evolution of the planetary orbit. In cases where there is an inclination between then stellar and planetary orbital planes, the planetary orbit will suffer an exchange of energy between inclination and eccentricity, with the semi-major axis remaining approximately constant, an effect first discussed by Kozai (1962). This mechanism has been explored in detail by Holman *et al.* (1996) and by Mazeh *et al.* (1996). Whether this effect is responsible for the large eccentricity of the planet around 16 Cyg B is unknown because of the large uncertainties about the parameters of the stellar orbit and the relative inclinations of the stellar and planetary orbital planes. Hale (1994) examined the question of coplanarity between the orbital and the stellar equatorial planes in solar-type binary systems. This study concluded that systems with large (100 AU) separations showed little correlation between the orbital plane and the stellar equatorial planes, while systems with separations less than 30-40 AU showed approximate coplanarity. For the specific case of 16 Cygni A and B, Hale estimated stellar equatorial inclinations of $43^{\circ}{}^{+47}_{-29}$ and $90^{\circ}{}^{+0}_{-34}$ respectively. While the orbital inclination of the binary is unknown, from the statistical results of Hale's study it is unlikely that it coincides with the rotational inclination of either star, and thus probably does not coincide with the original orbital inclination of the planetary companion to 16 Cyg B. Thus, this mechanism provides a quite plausible explanation for the large observed eccentricity of this object. Any additional observational constraints on these parameters would be of immense value.

An alternate possible scenario for the origin of the large planetary eccentricity is also tied to the formation of the planet in a multiple star system. Such systems often form as "trapezium" systems of several stars in a dynamically unstable configuration. A three-body gravitational interaction often will eject one object from the system, and will often bind the other two stars in a tighter binary orbit. The 16 Cygni system is now a triple star system, with a distant M dwarf companion to the G dwarf binary. It is quite possible that the system originally had some other component when it was formed. A three-body encounter between A, B, and this other, now ejected, star could have served to perturb the planet around B into its present large eccentricity orbit. Unfortunately, such a scenario is virtually impossible to prove.

Analysis of the photospheric lithium abundance may provide interesting additional constraints on the formation and early evolution of this system. Lithium is easily destroyed

by (p,α) nuclear processes at relatively low temperatures of a few million degrees, which can be reached at the bottom of the convective zone in G dwarfs. The lithium abundance of a solar-type dwarf can provide limits on the depth and extent of convective mixing of photospheric material in the formation and early (pre-main sequence) evolution of the star. Lithium in the sun is depleted by a factor of 100 relative to the meteoritic abundance. Observations by King *et al.* (1996) show that 16 Cyg A has a mean photospheric Li abundance of $\log N(\mathrm{Li}) = 1.27 \pm 0.04$, while the abundance of 16 Cyg B is $\log N(\mathrm{Li}) = 0.48 \pm 0.14$. The solar value, computed with the same analysis procedure, is intermediate between these two stars at $\log N(\mathrm{Li}) = 1.05 \pm 0.06$. We confirm, from the Lick spectra, that the Li 6707Å resonance line in 16 Cyg A is considerably stronger (W_λ = 12mÅ) than that in B. As was discussed in Section 2, the spectra of the Sun, 16 Cyg A, and 16 Cyg B are otherwise nearly indistinguishable. This difference in the Li abundance between 16 Cyg A and B most likely points to a difference in the mixing of the photospheres and the deeper layers of these stars, which is probably driven by rotation (Pinsonneault *et al.* 1990). Thus, it is likely that 16 Cyg A and B had a somewhat different angular momentum history, either a difference in the initial angular momentum or a difference in the rate at which the stellar rotation has slowed.

Stars of equal mass, age, and initial chemical composition may nonetheless differ in angular momentum. The angular momentum history of young solar-type stars is governed strongly by torques exerted on the star by the inner accretion disk, as is observed in pre-main-sequence (PMS) stars (Edwards *et al.* 1993). PMS stars with massive disks exhibit slow rotation rates due to the (presumably magnetic) coupling to the inner disk (Armitage & Clarke 1996). Observationally, slowly rotating young G stars exhibit lower photospheric Li abundances, and hence have burned Li more rapidly than the rapid rotators (Soderblom *et al.* 1993). This effect is opposite to that predicted by early models of Li depletion, involving meridonal circulation. More recent work by Martín and Claret (1996) shows that rapid rotation in contracting PMS stars can significantly inhibit the depletion of Li, in accord with observations. Thus, we now have a reasonably coherent connection between the presence of a disk, early stellar rotation rates, and Li depletion. The large spread in photospheric Li abundance at a given mass and age in well-studied young clusters is a result of the spread in rotation rates of these stars during their PMS phase. The rotation rates are, in turn, regulated by the disk mass (Strom 1994). Therefore, it may be possible to use the Li abundance of an older main-sequence star as a diagnostic of the mass of its protoplanetary disk, and hence of the planet-building environment. From this picture, we would expect that solar-type stars with large Li abundances for their mass and age were rapidly rotating in their PMS stage due to the lack of rotational braking by a massive proto-planetary disk. Conversely, a star being depleted in Li for its mass and age would

indicate slow PMS rotation resulting from the presence of a proto-planetary disk. This reasoning suggests that for stars of equal mass and age, one may rank their proto-planetary disk masses based on the current-epoch Li abundances. The sense of this is consistent with what we see in 16 Cyg A and B. We find significant Li depletion in 16 Cyg B, and this star has a 1.5 Jupiter mass planet at 1.6 AU which presumably formed in a massive protoplanetary disk which would have served to brake the stellar rotation. On the other hand, 16 Cyg A has a much larger Li abundance, indicating more rapid PMS rotation. We find no Jovian mass companion to 16 Cyg A, which is consistent with the lack of a massive protoplanetary disk to provide rotational braking for the star. If the Sun has an age similar to that of the 16 Cyg system, we would conclude that it had a disk intermediate between those of 16 Cyg A and B. Indeed, the major planet around the Sun is of lower mass and is farther from the star than in the case of 16 Cyg B.

Work at McDonald Observatory was supported by NASA grant NAGW-3990. The Lick Observatory program was supported by NASA grant NAGW-3182, by NSF grant AST95-20443, and by Sun Microsystems. We would like to thank Jeremy King and Jihad Touma for enlightening discussions. WDC is very grateful to the late Harlan J. Smith for his enthusiastic support and encouragement of the McDonald program during its early years, and for his faith that radial velocity techniques would find an abundance of planetary systems around nearby stars. We all wish that he could have lived to see this vision come true.

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This preprint was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— The combined Lick and McDonald radial velocities for 16 Cygni B. The triangles are from Lick data and the crosses are from McDonald. The solid line is the radial velocity curve from the orbital solution.

Fig. 2.— The combined Lick and McDonald radial velocities for 16 Cygni A. The symbols are the same as in Fig. 1. No radial velocity variation is evident in these data.

Fig. 3.— The relationship between eccentricity and minimum mass for the substellar companions (both planets and brown dwarfs) found so far.

Table 1. Comparison of Physical Parameters of the Sun with 16 Cygni A and B

Parameter	Sun	16 Cygni A	16 Cygni B	Reference
Spectral Type	G2V	G1.5V	G2.5V	
T_{eff} (K)	5770	5785±25	5760±20	Friel *et al.* 1993
$\log g$ (cgs)	4.44	4.28±0.07	4.35±0.07	Friel *et al.* 1993
Mass ($M_\odot$)	1.0	1.05±0.05	1.00±0.05	Friel *et al.* 1993
[Fe/H]	0.0	+0.05±0.06	+0.05±0.06	Friel *et al.* 1993
$v \sin i$(km s^{-1})	1.9±0.3	1.6±1.0	2.7 ± 1.0	Soderblom 1982
Rotation Period (days)	25.38	26.9	29.1	Hale 1994

Table 2. McDonald Relative Radial-Velocities of 16 Cygni B

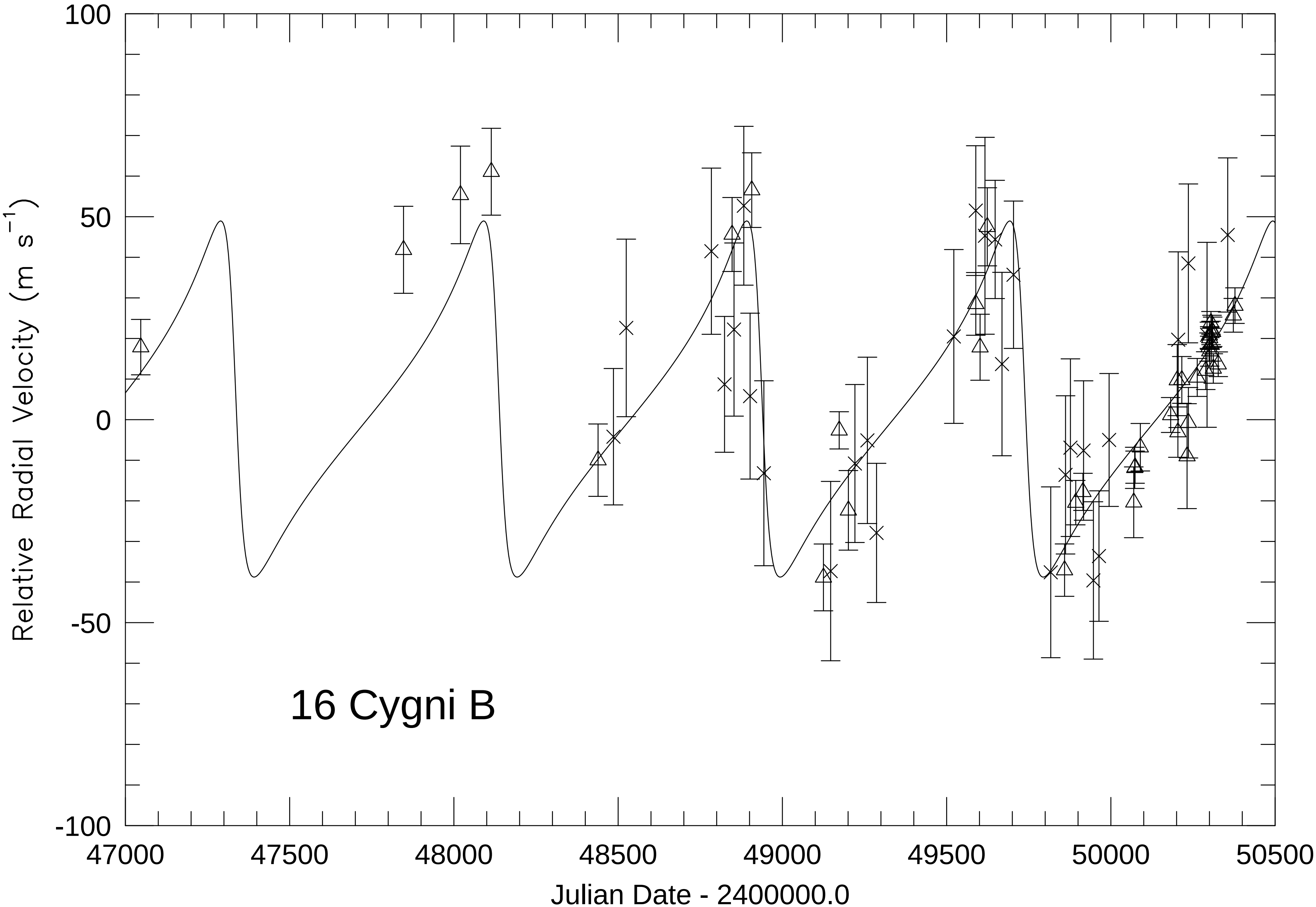
JD-2400000.0	V ($\mathrm{m\,s^{-1}}$)	σ($\mathrm{m\,s^{-1}}$)	JD-2400000.0	V ($\mathrm{m\,s^{-1}}$)	σ ($\mathrm{m\,s^{-1}}$)
48485.7305	-4.2	16.8	48524.6562	22.6	21.9
48783.8398	41.5	20.5	48823.8984	8.7	16.7
48852.7734	22.2	21.3	48882.5742	52.7	19.6
48901.6875	5.8	20.4	48943.6328	-13.2	22.8
49146.9102	-37.3	22.1	49220.7812	-10.8	19.5
49258.7500	-5.1	20.5	49286.6367	-27.9	17.1
49521.8984	20.5	21.4	49588.7305	51.5	16.0
49616.6602	45.3	24.2	49647.6289	44.4	14.6
49668.5430	13.7	22.6	49703.5508	35.7	18.1
49816.9023	-37.6	21.0	49861.9141	-13.6	19.5
49876.8438	-6.9	21.9	49916.7930	-7.6	17.2
49946.8125	-39.6	19.4	49963.7070	-33.6	16.1
49994.6055	-5.0	16.4	50204.9258	19.7	21.6
50235.9023	38.5	19.6	50292.7539	20.9	22.8
50355.6328	45.5	19.0			

Table 3. Lick Relative Radial-Velocities of 16 Cygni B

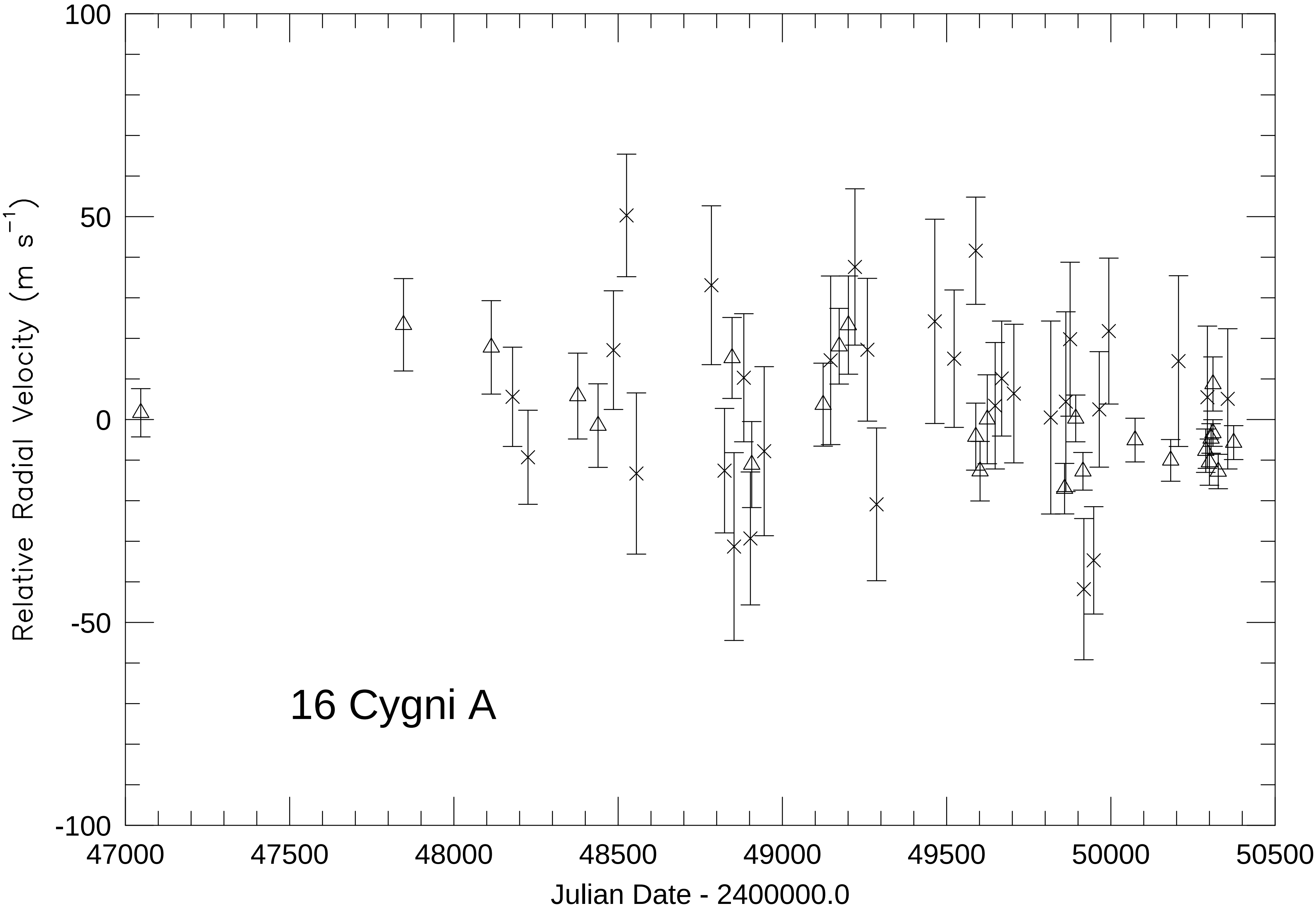
JD-2400000.0	V ($\mathrm{m\,s^{-1}}$)	σ($\mathrm{m\,s^{-1}}$)	JD-2400000.0	V ($\mathrm{m\,s^{-1}}$)	σ ($\mathrm{m\,s^{-1}}$)
47046.7695	17.9	6.8	47846.6758	41.9	10.7
48019.9531	55.4	12.0	48113.8242	61.1	10.7
48438.8750	-10.0	8.9	48846.8750	45.6	9.1
48906.6992	56.5	9.2	49124.9844	-38.9	8.2
49172.9062	-2.6	4.6	49200.8750	-22.3	9.8
49588.7422	28.5	7.7	49601.7656	17.8	8.1
49623.7266	47.5	9.6	49858.9844	-37.1	6.4
49892.9648	-20.4	5.5	49914.9688	-17.8	4.6
50069.5781	-20.4	8.7	50072.5742	-11.9	5.1
50073.5977	-11.7	4.0	50089.5938	-6.8	5.9
50182.0039	1.2	4.3	50202.0039	9.7	8.8
50203.9648	-3.1	6.2	50215.9336	9.8	5.8
50231.9219	-9.0	12.9	50235.9883	-0.8	8.7
50262.9023	10.4	4.7	50288.7578	12.1	4.7
50298.7852	17.9	3.5	50299.9414	20.8	3.2
50300.7305	20.1	2.8	50300.9375	16.9	3.7
50304.6758	23.9	2.8	50304.9492	21.4	2.9
50305.7539	18.5	4.0	50307.7969	21.8	4.0
50309.8008	21.6	3.6	50311.7695	12.6	3.6
50326.7734	13.7	3.0	50372.6836	25.7	4.2
50377.7031	28.1	4.4			

Table 4. Combined weighted Orbital Solution for 16 Cygni B

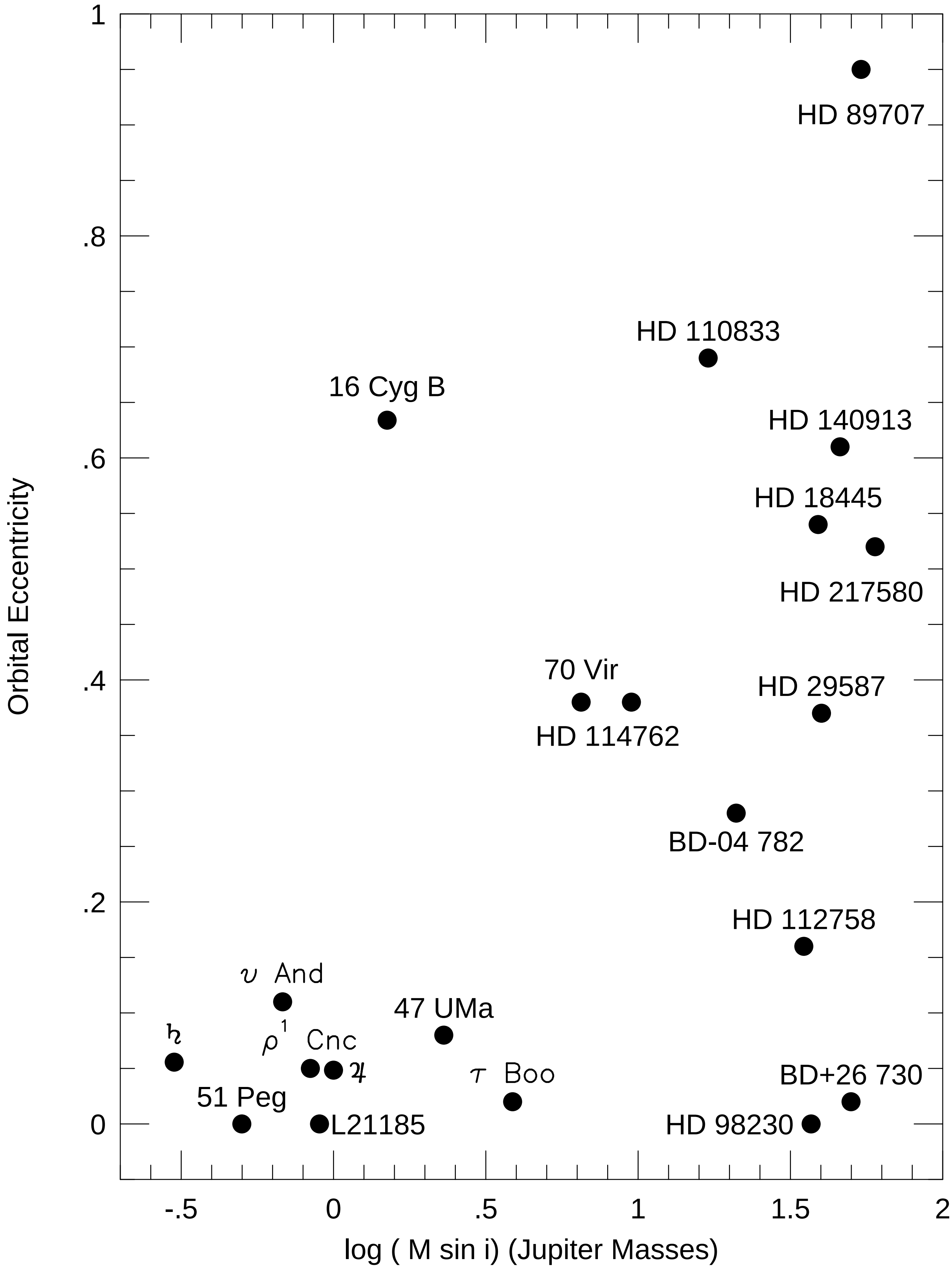
Parameter	Value	Uncertainty
Orbital Period P (days)	800.8	11.7
Velocity Semi-amplitude K ($\mathrm{m\,s^{-1}}$)	43.9	6.9
Eccentricity e	0.634	0.082
Longitude of Periastron ω (degrees)	83.2	12.7
Periastron Date T_0 (Julian Date)	2448935.3	12.0



100
50
0
-50
-100
47000
47500
48000
48500
49000
49500
50000
50500
Julian Date - 2400000.0
Relative Radial Velocity (m s^{-1})
16 Cygni B



100
50
0
-50
-100
47000
47500
48000
48500
49000
49500
50000
50500
Relative Radial Velocity (m s^{-1})
Julian Date - 2400000.0
16 Cygni A



Orbital Eccentricity
log (M sin i) (Jupiter Masses)
1
.8
.6
.4
.2
0
-.5
0
.5
1
1.5
2
HD 89707
HD 110833
16 Cyg B
HD 140913
HD 18445
HD 217580
70 Vir
HD 114762
HD 29587
BD-04 782
HD 112758
υ And
♄
ρ1 Cnc
♃
47 UMa
τ Boo
BD+26 730
51 Peg
L21185
HD 98230